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DEVELOPMENT OF A COARSE-GRID METHODOLOGY FOR HEAT TRANSFER CALCULATIONS IN PRISMATIC HTGR FUEL ASSEMBLIES

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1. ABSTRACT

This paper presents a coarse-grid Computational Fluid Dynamics approach, initially developed for light-water reactors and now extended to prismatic High-Temperature Gas-cooled Reactor fuel assemblies. This method, known as Subchannel CFD, combines the strengths of traditional subchannel codes and CFD. It offers CFD-like 3-D predictions at a substantially reduced computational cost, potentially allowing for cost-effective simulations at the reactor core scale.

2. INTRODUCTION

High-Temperature Gas-cooled Reactor (HTGR), a proposed Generation IV nuclear reactor, is gaining increasing attention due to its inherent safety, high thermal efficiency, and capability to generate high-temperature process heat. In 2022, the UK government selected HTGR for a development programme with the objective of having a demonstrator operational by the early 2030s [1]. The successful deployment of HTGR technology requires an in-depth understanding of its reactor physics, particularly the dynamics of coolant flow and heat transfer within the fuel assemblies in the core, and their impacts on the reactor efficiency and structural integrity. This relies on thermal-hydraulic analyses of the reactor system, which is traditionally performed using simplified approaches. With the recent advancement in computing capacity, more advanced Computational Fluid Dynamics (CFD) methods have started to play a role, exhibiting better features than traditional approaches. CFD can provide detailed 3-D predictions but requires substantial computing resources, which poses significant challenges for CFD to be used in real-world engineering applications.

In this study, we are aiming to extend a cost-effective coarse-grid approach, Subchannel CFD (SubChCFD) [2], to prismatic HTGRs. The core concept of the SubChCFD lies in the use of empirical correlations as substitutes for wall functions in the closure of the governing equations solved on the coarse grid. This ensures integral consistency of the results with well-calibrated friction and heat transfer correlations. More importantly, the use of a coarse mesh can significantly reduce the computational cost compared to the conventional CFD approaches.

3. METHDOLOGY

The MHTGR-350 benchmark, a representative prismatic HTGR designed by General Atomics [3], is used in this study to showcase the newly developed capabilities of SubChCFD. In order to effectively reduce computational costs,

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the design of the SubChCFD mesh is geared towards using coarse meshes for both the coolant channels and the graphite solid. Considering the repetitive spatial patterns within the fuel assembly due to symmetries of the hexagonal configurations, a mesh generation strategy is used, involving 3 steps: (i) identifying the smallest repetitive geometric patterns in the fuel assembly, (ii) generating sub-mesh for each of the patterns, (iii) duplicating, translating/rotating, and combining these sub-meshes to create the final mesh for the entire fuel assembly. Figure 1 shows a standard fuel assembly in the MHTGR-350 benchmark and the sub-meshes for its repetitive patterns.

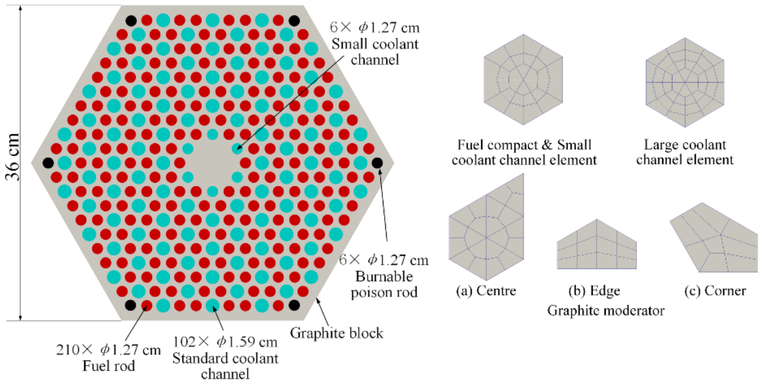

Fig. 1 Design of the coarse mesh for a HTGR fuel assembly. Left: cross-sectional view of the standard fuel assembly in MHTGR-350 benchmark. Middle: sub-mesh elements for smallest repetitive patterns.

To ensure a correct pressure drop in the coolant channels, calculation of the wall shear stresses are based on empirical friction factor correlations. The conjugate heat transfer is modelled using a so-called "internal coupling" approach, in which the energy equation for both the fluid and solid is solved using a unified matrix system. To make it workable with the coarse mesh, modified thermal exchange coefficients based on empirical Nusselt number correlations are implemented to the wall adjacent fluid cells, to ensure correct heat fluxes through the fluid-solid interfaces. The friction factor and Nusselt number correlations currently used in SubChCFD are shown in Equation (1),

$$C_f = \begin{cases} 64/\mathrm{Re} & \mathrm{Re}<2300 \\ 0.316\,\mathrm{Re}^{-1/4} & 2300 \le \mathrm{Re} < 3\times10^4 \\ 0.184\,\mathrm{Re}^{-1/5} & 3\times10^4 \le \mathrm{Re} < 10^6 \end{cases} \qquad Nu = \begin{cases} 4.36 & \mathrm{Re}<2300 \\ 0.021\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} & \mathrm{Re}\ge 2300 \end{cases} \tag{1}$$

4. CASE STUDY

The new development is assessed using a postulated fully developed flow in a fuel assembly of the MHTGR-350 benchmark with conjugate heat transfer considered. The SubChCFD model is created in 2-D based on the streamwise periodicity. The coarse mesh adheres to the meshing strategy illustrated in Figure 1. Additionally, wall-resolved RANS with the k-ω SST turbulence model is used for the same flow condition to provide reference results. All simulations are performed using the open-source CFD software Code_Saturne. Figure 2 shows the simulation results of temperature distributions. The overall patterns of the temperature contours predicted by RANS and SubChCFD exhibit good agreement. SubChCFD provides a slightly lower prediction of the peak temperature compared to the RANS predictions for the first rank of the fuel compacts near the centre of the fuel block.

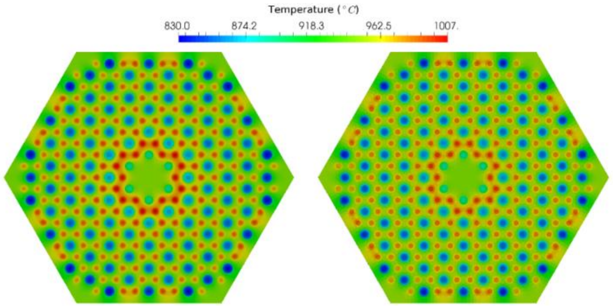

Fig. 2 Comparison of temperature contours predicted by the wall-resolved RANS model (left) and SubChCFD (right).

For a more detailed comparison, the temperature profiles are plotted over two lines shown in Figure 3. Line 1 is a 60° inclined line connecting the left bottom corner to the centre of the fuel block, while Line 2 is a vertical symmetry line. There are five temperature peaks in line 1, corresponding to the five fuel compact regions, and three temperature troughs, corresponding to the three coolant channels. SubChCFD closely predicts coolant temperatures compared to the RANS model, even with only 6 to 7 grid points across each of the coolant channels. In contrast, the wall-resolved RANS model often requires very fine mesh distributions near the channel walls. Surprisingly, the most significant disagreement between SubChCFD and the RANS model occurs in the solid domain at the fuel regions near the centre of the fuel block. On line 2, where no fuel regions, the five temperature troughs correspond to the five coolant channels. It can be seen that the asymmetric features of the transverse coolant temperature distribution across the centre and peripheral channels are well captured by SubChCFD, giving an advantage of the method over the traditional unit cell approaches, where the coolant channel is often modelled in 1-D.

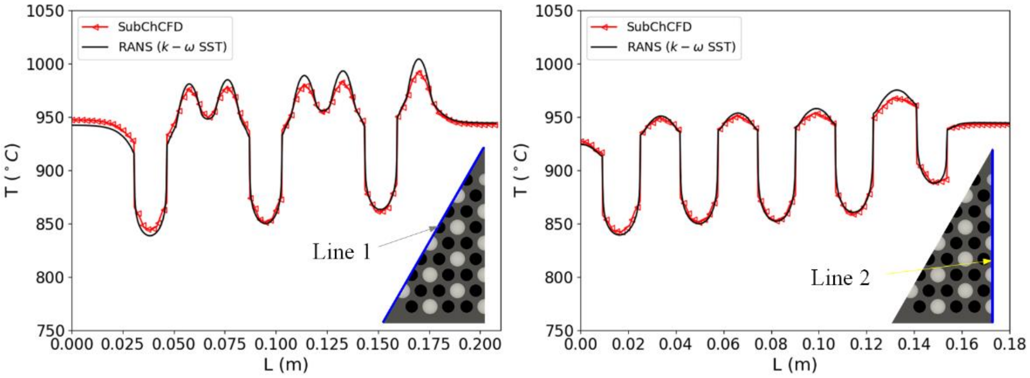

Fig. 3 Temperature profiles over 2 lines in the fuel assembly.

5. CONCLUSIONS

The main aim of this work is to extend a coarse-grid approach SubChCFD, originally designed for light-water reactors, to prismatic HTGR fuel assemblies. To accomplish this, several new features are introduced into the exiting SubChCFD framework, including the ability to handle new geometries relevant to prismatic HTGR fuel designs, the incorporation of new empirical correlations for closure modelling of the governing equations, and conjugated heat transfer functionality, essential for modelling HTGR fuel assemblies. The new development is assessed using a test case centred around the General Atomics MHTGR-350 benchmark with multi-hole type of fuel elements. SubChCFD exhibits excellent capabilities in simulating thermal-hydraulic phenomena under HTGR conditions, producing results of comparable quality to RANS approaches while employing a significantly coarser mesh. In the next step, SubChCFD will be further developed to handle transient processes and natural convection within the HTGR core by incorporating more sophisticated correlations that can account for flow acceleration and buoyancy effects.

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